DISCUSSION ON "WAVE GUIDES IN ELECTRICAL COMMUNICATION"*

WIRELESS SECTION, 3RD NOVEMBER, 1943

Mr. A. J. Gill: The time is most opportune for the publication of a paper on wave guides, and it is a pity that owing to the exigencies of the war the more recent developments in this interesting and increasingly important subject cannot be disclosed now.

I happened to be in the United States in 1936 and spent about a fortnight at the Bell Laboratories in New Jersey, where Dr. Southworth was working; during that period I visited his laboratory and saw some of the work which he was doing.

The most interesting thing about the wave guide is that the quantity of energy transmitted does not depend upon the metallic conductor. The upper limit of energy would be the amount of energy which would cause such a voltage gradient as to break down the air in the tube. If the tube could be evacuated, presumably an infinite amount of energy could be transmitted.

In Dr. Southworth's original paper it is mentioned that on the H_{10} wave, according to theoretical computations, one should get a lower and lower attenuation as the frequency increases. The author confirms this, but explains that the wave guide must be absolutely circular; as no wave guide is absolutely circular, this interesting phenomenon is not likely to occur in practice.

In the Post Office Engineering Department we have not had much occasion to use wave guides, but have made some experiments with some of the largest conducting tubes in existence—the tubes of the London Underground Railways. In 1939 we made some experiments designed to find out whether these tubes behaved as wave guides, and we chose a frequency well within the translucent range. We found that although the wave was propagated and its polarization was apparently preserved, the tube itself did not behave as a wave guide. We obtained fairly good transmission when the tube was straight, but the wave did not like to go round corners: on a curved tube the transmission range of our equipment was only about half a mile. It is not clear why this should have been so, for the tubes are made of cast iron and the sections are bolted together and usually caulked with lead at the joints, so that these should have a good metallic connection.

One naturally speculates about the future of wave guides. They will clearly be used for ultra-short-wave radio equipment, both for the transmission of energy from the transmitter to the aerial, and also for direct radiation where aerials are not employed. They may also be used for receiving purposes. One cannot help wondering whether they will be used as a substitute for either balanced or coaxial lines in line communication. If so, energy will have to be produced at very much higher frequencies than at present, in order to bring the conductors which could be used within a convenient size for putting into under-

* Paper by JOHN KEMP (see 90, Part III, p. 90).

ground ducts. I think it will be some time before this is practicable. Other problems which will have to be solved are those of modulation and frequency-control. If precise frequency-control were possible, beat methods of changing the frequency could be used and thus the processes of modulation and demodulation would be facilitated; but precision control is not at present available on frequencies within the 1 000-Mc/s range.

Some of the repeaters described in the paper make use of resonating cavities or of spaced aerials. Those with resonating cavities are very suitable for fixed frequencies, but it is not possible to convey intelligence on a single frequency; a band is required, and the great attraction of wave guides lies in the possibility of transmitting over them a very wide band of frequencies. It seems questionable whether the repeaters described in the paper would function satisfactorily over a wide band because of the resonating cavities associated with them. One repeater, shown in Fig. 34, contains pairs of aerials in which discrimination between forward direction and return direction is derived by spacing aerials a quarter wavelength apart. There again it would be possible to obtain perfect balance at one frequency, but at other frequencies there would be feedback between the transmitting and receiving aerials; with a band width of, say, 2% there would probably be a feedback of about − 60 db, so that if the gain of the repeater were of this order singing would be liable to occur. One cannot help feeling therefore that the repeater problem has not yet been solved.

Dr. H. R. L. Lamont: Many of the devices described in Section 3 of the paper are taken from patent specifications, and therefore their practical utility in the form shown should not be accepted without some reservations. Their design is not quite so simple a matter as one might think from reading the paper. Not only has one to make an element which will perform the required task—that is, select or transform the wave—but one has also to make an element which will match the wave guide at the frequency in question, and that may be difficult for an extended frequency band such as is required in some of the uses envisaged. A fuller discussion of the principles involved in this question of matching would have been useful.

I must disagree with the author's strictures on Huygens's principle in Section 4.1.4. The failure of that principle to explain certain experimental results was a failure, not of principle, but of method, because the mathematical formulation of Huygens's principle normally used in optics is not adequate for cases in which the aperture is comparable with the wavelength, and the modifications made to the simple optical theory in an attempt to overcome this difficulty were not in fact sufficient for the purpose. If, on the other hand, one uses the more rigid theory derived by Kottler from Huygens's principle, one gets exactly the same result as is obtained by Schelkunoff's equivalence principle quoted in the paper.

Mr. E. H. Ullrich: There are two points connected with the paper which I should like the author to amplify.

First, dealing with the resolution of waves in guides into plane waves in Section 2.5.5, the author says: "Attractive as such resolutions may be for illustrating the characters of phase and of signal velocities, they must be regarded as mathematical notions without physical counterparts, and their application therefore requires great care." I should like to ask the author why such resolutions must be regarded as mathematical notions only, and what pitfalls we are likely to fall into if we regard them as anything more.

My second point relates to *(d)* in Fig. 13: Can the author give any indication of the magnitude of losses in cavities in general, but more particularly where there is a change in the dimensions of the guide, as in *(d)*, Fig. 13?

Dr. R. L. Smith-Rose: Some newcomers to the art of radio-communication may have the impression that the idea of guiding waves along conductors is a new one, but on referring to the literature of 30–40 years ago it will be realized that this subject was even then a very controversial one, particularly in relation to the manner in which the waves were propagated round the curvature of the earth. Some held the view that the waves were guided round by the conducting material of the earth, but in due course it was shown that the ionosphere was necessary to guide the waves suitably "round the corner." Clearly, the ionosphere on the one hand and the surface of the earth on the other, form a proper wave guide, having due regard to their separation and the appropriate wavelengths. I should like to emphasize that there are still some unsolved problems connected with the manner in which waves are propagated along the earth's surface.

In Section 2.5 the author applies the terms phase and group velocities to the propagation of radio waves down hollow guides. These terms are, however, strictly only applicable to transmission through a dispersive medium in which the velocity varies with the wavelength. In a hollow wave-guide the medium is air and therefore substantially non-dispersive, and the phase velocity is independent of the wavelength. Because the path of the waves down the guide is of a zigzag nature following successive reflections from opposite walls, it may be convenient to speak of an effective or "signal" velocity, but this should not be confused with the true meaning of group velocity.

In Fig. 9 the author suggests that a peculiar wavelength is obtained if the waves on the surface of water going along a canal are observed through the space between two boards placed slantwise across the canal. One might similarly suggest that a bird flying along the canal at the speed with which the waves are travelling, and merely looking at the water vertically underneath, would come to the conclusion that the surface was perfectly calm and free from any wave motion. Is it not an essential principle that the wavelength must be measured between corresponding points in successive portions of the wave in the direction in which the waves are travelling?

It is interesting to compare Fig. 2, showing the attenuation for various diameters of wave guides, with the corresponding attenuation for the best type of coaxial cables available to-day. The coaxial cable, which was laid prior to the war between London and Birmingham for the transmission of a carrier of television frequencies, had an attenuation of about 5 db per mile. This value is well down in the bottom corner of the diagram, so that it compares favourably with the attenuation of the best and most appropriate diameters of wave guide for the much shorter wavelengths.

In Section 2.5.4 the author says: "Energy is usually assumed to flow at right angles to both the electric and the magnetic forces of the field." Is not that assumption perfectly correct? If one has to deal with the superposition of several waves, is the validity of that fundamental principle altered? One has to be very careful as to what is being compared when considering the direction of flow of energy in a multiplex wave system as compared with the electric and magnetic forces of the component waves. Even the author shows no reason to doubt the validity of that assumption, but the sentence which I have quoted would appear to imply that he thinks there was reason to do so.

Dr. R. F. J. Jarvis: I agree with Dr. Smith-Rose that in Fig. 2 a comparison ought to be made with the coaxial cable. On a 2-in diameter coaxial cable the attenuation will be less than the minimum attenuation for the H_{11} wave in a 2-in diameter guide at frequencies up to 1 000 Mc/s. It might be easier to get the gain at frequencies up to 1 000 Mc/s than it would be to get the gain at the higher frequencies required by the guide, and 50 broad-band television circuits could be accommodated in the 1 000-Mc/s band. With the coaxial cable, one can ensure that

only one type of wave is transmitted, namely the principal wave, and that this wave continues in the same form; but some theoretical work carried out before the war showed that certain waves did not continue to be transmitted along wave guides in the same form, or that they set up waves which would interfere with the main wave, so that one might get a much higher attenuation or irregular frequency response.

I agree with Mr. Gill about the importance of the repeater, a matter on which the information given in the paper is very meagre. Of the first repeater referred to, the triode type, the author says that the application seems to be severely restricted by the transit time of the electrons. Does he think that the Klystron* type will be better in this respect?

If full use is to be made of the frequency spectrum, without using different repeaters for different parts of the available spectrum, it will be necessary to have very wide-band repeaters. To this end it will be necessary to have a repeater valve with a very high effective slope, because the output impedance or inter-stage coupling impedances will necessarily be low.

The author does not mention the type of repeater in which the frequency is changed to a lower value at the input end, amplified at the lower frequency, and then changed back again to a higher frequency at the output end. In this way it might be easier to obtain amplification over the band of, say, 3 000 to 3 500 Mc/s than it would be if direct amplification of this frequency band were attempted.

Mr. L. Jofeh: There are a few points which I should like to raise in connection with this paper, and which have not been touched on to any great extent by other speakers. The first is that the value of the paper would have been considerably increased had some of the more important formulae been included as an appendix. The second point is that insufficient space is devoted by the author to the important concept of impedance as applied to wave guides.

The third point concerns the question of phase velocity. The author's treatment of that subject seems to suggest that there is something odd about the whole thing. A phase velocity greater than that of light is, however, commonly experienced, even in radio reception, as may be seen if one is sufficiently close to a transmitting station for it to be at an appreciable angle of elevation; for in that case the direct wave from the transmitter and the reflected wave from the ground add up to produce a pattern which has a phase velocity greater than that of light.

In Section 2.5.5 the author mentions "mathematical notions without physical counterparts." It is nevertheless the case that if one is considering convertors, for example, or bends or anything of that sort, the reality of the two components of the combined wave is very forcibly brought home.

Dr. K. R. Sturley: In his account of the theory of wave guides the author wisely makes it clear that a longitudinal electric force in a wave is not a very uncommon phenomenon. We have an example of this in a vertically-polarized wave passing over an imperfectly conducting earth; the electric field is tilted, resulting in a longitudinal, as well as a vertical, electric force.

I should like to mention that a very clear exposition of the subject of phase and group velocity was given recently in *Electronics* (1943, **16**, March, p. 76). I do not like the term "phase velocity," because it does not appear to convey what is intended; the term "crest velocity" would be much more helpful from the teaching point of view. The same is true of "group velocity." The author seems to have appreciated the objection to that term, because he has tried to use the term "signal velocity," but even that is not sufficiently explicit, and probably "modulation velocity" would be nearer the mark.

Is it strictly correct to refer, as is done, for example, on page 97, to two electric forces being present in the wave? Surely it is the same electric force, but in one case it happens to be transverse and then, 90° ahead, it happens to be longitudinal.

The behaviour of the grating discriminator, in Section 3.1.4, is more conveniently explained by considering the magnetic rather than the electric component. For instance, if we take the case of the H_{01} wave with the longitudinal component along the axis of the guide, we see that a circular grating is really a short-circuited turn which is absorbing the magnetic energy.

Section 3.2.2 contains the statement: "If a simple numerical relation exists between the impedances of the two gratings and the characteristic impedance of the guide, the wave reflected from the first grating is annulled by that reflected from the second." What is meant by "a simple numerical relation"?

I was puzzled on first reading the paper as to how a guide could produce waves of other modes from a wave of given mode, and it may be of interest to others to note that this can be shown by referring to Section 3.5.2, on baffle-plate convertors. If we add the pattern of the electric force of an H_{01} wave to that of an H_{11} wave (Fig. 4), we find that over one semi-circular section of the guide the fields from the two waves cancel, and over the other they add, leaving a resultant wave of a shape approximating to the half-section H_{11} wave shown at the top right-hand corner of Fig. 21. Similarly the middle left-hand diagram of Fig. 21 can be built up by the addition of the electric fields of the H_{11} and H_{21} waves of Fig. 4, together with the radial electric field of an E_{01} wave.

Dr. T. H. Turney: I should like to raise the question of impedance in wave-guide theory, because it seems to me that a discussion of impedance is needed. What is meant by impedance in ordinary work? It is a term involving the division of a voltage by a current; where the voltage is unknown, but the wattage flowing along the guide and the current in the guide can be calculated, it is legitimate to determine the equivalent voltage as the quotient of W divided by I, and to use this figure with the current to calculate an impedance. But, and here is the crucial point, the current used for dividing into the wattage must be of the nature of total current. Mr. J. R. Carson of the American Telephone and Telegraph Company was, I believe, the first to make an impedance calculation on these lines. For the E_0 type of wave the calculation seems to me as successful as it is ingenious, since the whole of the ether-displacement current along the guide completes its circuit by the metal sheath of the guide itself. Thus if the sheath current is calculated, as done by Carson, this sheath current is the total current and may be called *the* current, ranking with the current in a telephone line.

When, however, it comes to the case of the remarkable H_0 or magnetic wave, the calculation for impedance based on the current in the sheath is surely misleading. The main current does not flow through the sheath as it does in the electric or E-wave case. The main current is in circles with paths wholly in air. It is true that there is a sheath current, but it is not a measure of the transmitted energy. It is a skin-effect current; a sort of high-frequency loss. That is why this wave can have such low attenuations. As the frequency is raised, the skin effect becomes more pronounced, the penetration is reduced and the impedance looking into the metal rises, meaning that the loss is reduced. This is very important, for it means transmission with fewer repeaters at no very distant date, and may probably oust the coaxial cable.

The impedance of a magnetic wave seems to me to need a separate calculation. The graph showing this rising towards infinity is surely wrong, in that it is based on a loss current and not on the main current. The magnetic wave may be treated by asking what wattage flows along the tube and what alternating

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pressure would be set up in a little Hertz resonator placed in the nodal circle of the guide. This circle, embracing all the flux in the guide, seems to me to be a correct start for the calculation.

From a practicable point of view impedances fall into two groups: First, at the end of the guide there is always surely a piece of wire or a loop, that is an element of a conventional circuit supplying (or in the case of the receiver, picking-up) a conventional voltage (or current). The impedance of these transmitter and receiver elements looking into the guide must be calculated.

Secondly, there is the problem of joining parts of guides together without reflection, which requires expressions concerning the wave itself and not the circuit elements at the ends. Calculation of impedances may perhaps be performed by saying: What amount of reflection takes place? Find it by experiment and so define the impedance of a device, such as a filter, to the flow of wave energy.

Schelkunoff in an article on impedance, points out that the quotient of force by velocity in mechanics has the nature of an impedance. Also that in a plain wave with E the electric force and H the magnetic force at right angles, E/H is an impedance having a direction at right angles to both.

If the vector E_x divided by H_y is equal to E_y divided by H_x then $\frac{E_x}{H_y} = \frac{E_y}{H_x}$ is the impedance in the Z direction. This relation means that the ratio $\frac{E_x}{E_y} = \frac{H_y}{H_x}$, namely that the two components of electric force along the x and y axes stand in the same ratio as the two components of magnetic force along the y and x axes. This, in turn, means that the resultant vector of E is at right angles to the resultant vector of H, because the two parallelograms, one for finding the resultant of E and the other for the resultant of H, are similar but one is lying on its side.

Doing this for the H_0 wave gives $\frac{E_r}{H_\theta} = \frac{j\omega\mu}{\rho c} \times \frac{\rho}{j\beta} = \frac{\omega}{\beta c}$

The division being independent of ρ makes E/H independent of the radius, so it is the same impedance all over the cross-section of the circular guide. In these circumstances the impedance expression E/H seems to be entitled to be called *the* impedance.

$$\text{For H-waves, } Z_0 = \left(\frac{\mu}{\kappa}\right)^{\frac{1}{2}} \frac{\lambda \text{ in tube}}{\lambda \text{ in free air}}$$

In M.K.S. units, μ is $4\pi \times 10^{-7}$ and κ is $\frac{1}{36\pi} \times 10^{-9}$ so that

$$\left(\frac{\mu}{\kappa}\right)^{\frac{1}{2}} = 120\pi = 377 \text{ ohms}$$

Since the wavelength is very long near the cut-off, the impedance is infinite at cut-off, falling to 377 ohms. This gives a graph which is the inverse of the one based on current in the tube. The two waves E and H have the same impedance at frequencies well above the critical frequency of the guide. Near the critical frequency, the impedance of the E-wave is low and that of the H-wave is high. Here E and H are not volts and amperes, though related to them.

When it comes to exciting the wave in the guide, some ordinary apparatus, such as a short piece of wire or else a circular resonator, must be used. There must be a relation between voltage in this, and the E in the wave. Such relations are surely important, and the impedance of the sending device in position in an infinitely long guide is an important figure, as also is the ratio of energy transferred from the wire or loop to the guide.

Is it correct to say that the impedance of a wave guide at frequencies well above cut-off is 377 ohms, unaffected by diameter? A larger guide may have a larger area for the circulatory currents, but the length of the circle is larger, so that the impedance defined by E/H remains the same.

Prof. C. L. Fortescue: In Fig. 17, the lines of electric force are shown as continuous loops which are all much closer together in the conductor than in the space outside. It is generally understood that where lines of force are close together the field is intense, but it is not clear how the field can be more intense in this conductor than it is in the space outside.

I am particularly interested in this point because I have held the opinion that there is no fall of potential over the surface of the conductor if it has infinite conductivity, but my physicist friends disagree. I would like to ask the author whether, in his opinion, there is a difference of potential over the surface of the conductor, because if such a difference of potential exists then, when a long wave is spreading out from an aerial between the Heaviside layer and the earth, there will be hills and dales of potential advancing over the surface of the earth. Is this so?

Mr. Gill referred to the future of wave guides, and I suggest that this is all a question of the utility of the waves for which they are suitable as transmitters and of the effectiveness with which those waves can be generated.

Mr. W. E. Willshaw: Previous speakers in the discussion have tended to regard wave guides as quite distinct from other means of propagating energy, and particularly as distinct from concentric lines. We should, of course, realize that a concentric line, working in its normal low-frequency mode, really uses one of the modes of propagation of waves in a wave guide of a concentric-line form.

As an example of the relationship between wave-guide and concentric-line propagation, if we take a rectangular H_{02} wave guide (a wave guide of rectangular section with a full-wave variation of electric intensity across the section of the guide), bend its section round in a circle and remove the barrier, we obtain a concentric line. We are permitted to remove the barrier because the electric forces on the two sides of the barrier are zero and currents on each side are equal and opposite.

The usually-quoted figures for characteristic impedance, which are of the form given in the curve of Fig. 7, have no practical significance. We ought to take the ratio of the transverse electric to the transverse magnetic fields as the characteristic impedance, for this quantity is directly applicable to the characteristic impedance derived in the same way in the concentric-line case. This is particularly important, because one of the main uses of the conception of characteristic impedance concerns the determination of reflections at surfaces at which a dielectric is changed in a wave guide; the reflections which take place there are a function of the different characteristic impedances defined in that way on either side of the surface.

Capt. A. K. Wickson: May I suggest that the size of a wave guide for a given frequency could be reduced without excessive attenuation, by the addition of closely-spaced capacitive loadings along the length of the guide?

Mr. R. J. F. Howard: A better analogy for phase and signal velocity than the one used by the author is that of a sea wave breaking at an oblique angle against a sea wall. Viewed from a distance it appears that this phenomenon is happening at high speed, but when one approaches the wall one sees that the wave is moving relatively slowly. This analogy was given by H. H. Skilling (*Electronics*, 1943, **16**, March, p. 80).

I should like to refer to the question of nomenclature in regard to the E- and H-waves. The Americans are now using "TM" (transverse magnetic) and "TE" (transverse electric), so already

we are getting two distinct forms of nomenclature. Some standardization of these terms is desirable.

Dr. E. B. Moullin (*communicated*): May I suggest that a clear understanding of the behaviour of wave guides can be assisted by paying explicit attention to the conduction current in their walls: in the established treatment, this current appears only implicitly and as a derivative. An electric field always appears to me as a sort of disembodied spirit until it has been related to the electric charge from which it derives its being. It is only on the walls of the wave guide that electric charge and current can exist and move; hence I submit that we should be prepared to focus all our attention on them.

In essence, our problem consists in applying the inverse-square law (suitably generalized by means of L. Lorentz's delayed potentials) to calculate the field due to specified currents and charges on the walls of certain metal tubes. I hope I can make my point of view clear by means of the following example. Let A and B in Fig. A(i) represent the plan view of a pair of

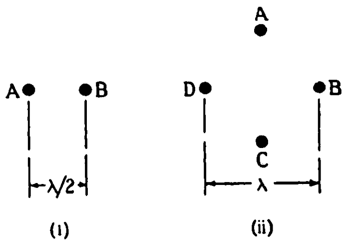

Fig. A

aerials carrying equal and co-phased currents: then it is well known and obvious that the field at a distant point will be zero in the directions AB and BA if the distance AB equals $\frac{1}{2}\lambda$. Again, if A, B, C and D in Fig. A(ii) represents the plan view of four aerials carrying equal and co-phased currents, then consideration will show the field is zero along both diagonals, if the diagonal of the square is equal to λ. Similarly, if six aerials are arranged at the corners of a regular hexagon, it can be shown the field along each of the three diagonals is zero if the length of the diagonal is $0\cdot72\lambda$.

Proceeding in this manner it should be obvious that aerials can be set round a regular polygon, so that there are as many bearings as aerials on which the field is zero; and, finally, if the ring of aerials becomes a complete tube, the field in the equatorial plane can be zero everywhere if the circle has the correct radius. A solution by means of a vector polygon is given in Fig. 6 of my paper on radiation resistance,* and according to it the radius should be $\frac{3}{8}\lambda$. An analytical solution is straightforward and gives the condition that $J_0\left(\frac{2\pi R}{\lambda}\right) = 0$, which occurs when $\frac{R}{\lambda} = 0\cdot384$ (compare with $0\cdot375$ by graphical solution). Though such a ring of half-wave aerials would give zero field everywhere in the equatorial plane, there would be a small field at high angles of elevation and hence the radiation cannot be zero, though it is small.

Section 3 of my paper on the screening properties of a cage† deals with the field outside a tubular current of infinite length, and Equation 9 of it shows that the field is zero everywhere if $J_0\left(\frac{2\pi R}{\lambda}\right) = 0$: the reason for this occurrence should now be plain from the approach from a ring of aerials. At this critical condition, conduction current flows axially along the walls of the tube and its circuit is closed by the displacement current inside the tube, since destructive interference has made the external field zero, and there is no radiation. If we wish to transmit power by conduction current flowing axially along the walls of a tube, obviously it is essential that the radiation be zero, or otherwise the attenuation will be large; accordingly the tube of current must have just that radius for which the radiation is zero. The smallest possible radius is when $J_0\left(\frac{2\pi R}{\lambda}\right) = 0$ and then there must be no change of phase along the axis of the tube; if there is periodic change of phase, the tube must be somewhat larger still. Here then is a complete general description of the E_{01} mode in a circular guide, starting from the current in its walls; which in my view is the essential physical reality.

Let us approach the rectangular guide in the same general manner. If a uniform current density i flows in an infinite flat sheet, it is easy to show that the field at distance x is expressed by the equation:

$$\frac{E}{2\pi i} = \cos\frac{2\pi x}{\lambda} + j\sin\frac{2\pi x}{\lambda}$$

With reference to Fig. B, let YY′ be the trace of an infinite plane standing perpendicular to the paper and with current

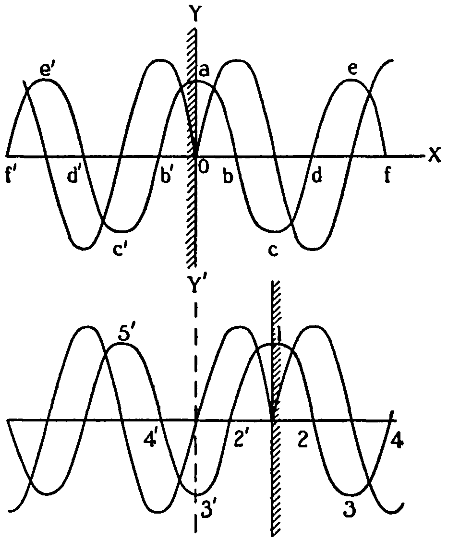

Fig. B

flowing along the Y axis: the curve abcdef and ab′c′d′e′f′ depicts the component of electric field which is in phase with the current density; its direction is parallel to the current flow. The other sinusoid in the same figure depicts the quadrature component; it is drawn slightly higher merely to distinguish it. The lower picture in the same Figure is a repetition of the upper, but displaced $\frac{1}{2}\lambda$ to the right. If two parallel sheets carrying a similar density are displaced by $\frac{1}{2}\lambda$, the resultant field will be that obtained by taking the arithmetic sum of the sinusoids in the two pictures.

It may be seen that the arithmetic sum of the curves c′b′abc and 3′2′123 is zero everywhere, and that the quadrature components neutralize everywhere, save in the space between the two sheets and there they add. Thus it is obvious that the external field is zero only if the separation is $\frac{1}{2}\lambda$, and then it is

* "The Radiation Resistance of Surfaces of Revolution, such as Cylinders, Spheres and Cones," *Journal I.E.E.*, 1941, 88, Part III, p. 50.
† "Screening Properties of a Squirrel Cage of Wires," *ibid.*, 1944, 91, Part III, p. 14.

$\frac{E}{4\pi i} = j \sin \frac{2\pi x}{\lambda}$ between the two parallel walls. If the separation is less than $\frac{1}{2}\lambda$, there must be radiation and hence attenuation in a wave guide. If the phase of the current density is periodic in the Z direction, then the wavelength will exceed λ when measured in the X direction, for the reason illustrated so clearly by Fig. 9 of the paper, and then the separation must exceed $\frac{1}{2}\lambda$ in order to annul radiation.

All the classic work on wave guides starts and ends without explicit reference to the original source of power, and this has to be introduced and explained as an afterthought, as is done by Figs. 17, 18, etc., of the paper. Now consider Fig. C, which

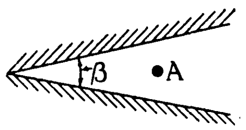

Fig. C

represents an aerial A in a V reflector of angle β. The solution of this problem is straightforward in terms of images and from start to finish would include the current I in the aerial. In the special case when the angle β tends to zero, the aerial is often forgotten and a special term, namely "wave guide," is introduced to describe this simple reflector system. I suggest that if wave guides are consciously recognized as a particular and limiting case of an aerial with reflector, then some people will discover that they are on old and familiar ground after all.

I have not much sympathy with attempts to define and measure the impedance of a guide (Section 2.4). It is only a hang-over from cable practice, and even there, I submit, it has arisen gradually from rather loose thinking. What we want to know is the impedance of an aerial or pair of aerials (or a loop) inside a guide. This arises naturally in the treatment described by Fig. C and is readily calculable for it. Why strain the impedance concept to apply to the walls of the reflector?

Mr. J. E. Taylor (*communicated*): The interest aroused by the rather scanty information which has been received in the last few years of this new development in wave propagation, amply justifies this paper.

In regard to the physical side of the matter and its representation in diagram form, I rather doubt the idea which seems to be conveyed in Fig. 17 as to the manner in which the waves are launched from the supply cable into the guide. From these diagrams, it seems that the waves in the supply cable are directly swept off the cable into the guide. If this were so, any kind of wave of any length could similarly be launched; this, of course, does not happen. The tendency for a wave reaching the end of an open circuit is for its magnetic component to be converted into the electric form together with arrest of the wave. For a closed circuit, it is the magnetic component that persists at the expense of the electric. In either case a backward wave is set up. In the open circuit the backward wave has a reversed magnetic component implying a hiatus of a half-wave or semi-oscillation in the propagation. The next succeeding forward half-wave interferes, annulling the electric component in the end standing field, and is in turn arrested with conversion of wave energy into the magnetic form. This means that an oscillation is set up at the conductor end, which is capable of radiating into the guide as a forward wave but with a phase missing. It would seem that the diagrams do not indicate this missing phase. In this principle of regeneration at the cable end lies the reason for adjusting the wave-length to suit the dimensions of the guide. I would put it as a general principle that, when a wave is arrested, it becomes an oscillation if conditions permit; that is, if its energy is not otherwise disposed of.

In Section 2.5.5, longitudinal electric and magnetic forces in the guide are referred to in relation to what are commonly known as the Poynting vectors, and a resultant wave is suggested which could be considered as zigzagging athwart the guide with a speed *averaging* that of light. Suggestions that energy can be translated with a speed exceeding that of light, useful as they may be in the mathematical treatment, do not tend to clarify the physical explanation. Presumably, the suggestion applies even when the guide is assumed to have perfect conductivity, in which case it is generally argued that the signal velocity would be that of light and the attenuation zero. Similar longitudinal forces are met with in free space, as when a conducting obstacle casts a shadow and the waves are then flanked by such forces. In that case they can be considered as contributing to diffraction of the waves.

[The author's reply to this discussion will be found on p. 154.]